Soft-sediment deformation structures
and palaeoseismic phenomena
in the South-eastern Baltic Region

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Large-scale glaciotectonically-deformed Pleistocene sediments with deformed layers sandwiched between undeformed layers, Baltmuiža site, Western Latvia

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Highlights

- Sandwich-like layers with injection structures and load casts.
- Small-scale soft-sediment deformation structures (abbr. SSDS) within large-scale glaciotectonically-deformed sediments.

Study area

The Baltmuiža site is located in the Western Latvia, Piejūra Lowland, Piemare Plain, 6 km to NE from Pāvilosta village. The outcrop is located in an upper part of coastal cliff (Figs 1 and 2). The area was completely covered by ice-sheet during the Late Weichselian glaciation, and became ice free ca. 14 ka ago after ice-sheet retreated from the Valdemārpils ice-marginal zone (Zelčs et al., 2011). After deglaciation, this area was completely submerged under various stages of the Baltic Ice Lake (Grīnbergs, 1957). The upper part of Quaternary sediments consists of Late Weichselian till (glacial diamictons) partially reworked by waters of the Baltic Ice Lake. Below the till are located Middle Weichselian lacustrine silty and sandy sediments (OSL age 26±2.6 ka after Saks et al., 2012a). Aforementioned lacustrine sediments have underwent a heavy diapirization during the retreat of Late Weichselian glaciation. Individual diapir width reaches up to ca. 150 metres and height ca. 30 metres (Saks et al., 2012b). The total thickness of Quaternary sediment cover is 70 m and they are underlain by Middle Devonian sandstones of the Gauja Regional Stage. The crystalline bedrock is located in the depth of 1.4 km. The Baltmuiža site is located on a known fault in crystalline bedrock that is not penetrating the sedimentary cover, whereas 10 km eastwards from the site is located a fault traceable in Ordovician sediments (Nikulin, 2011).

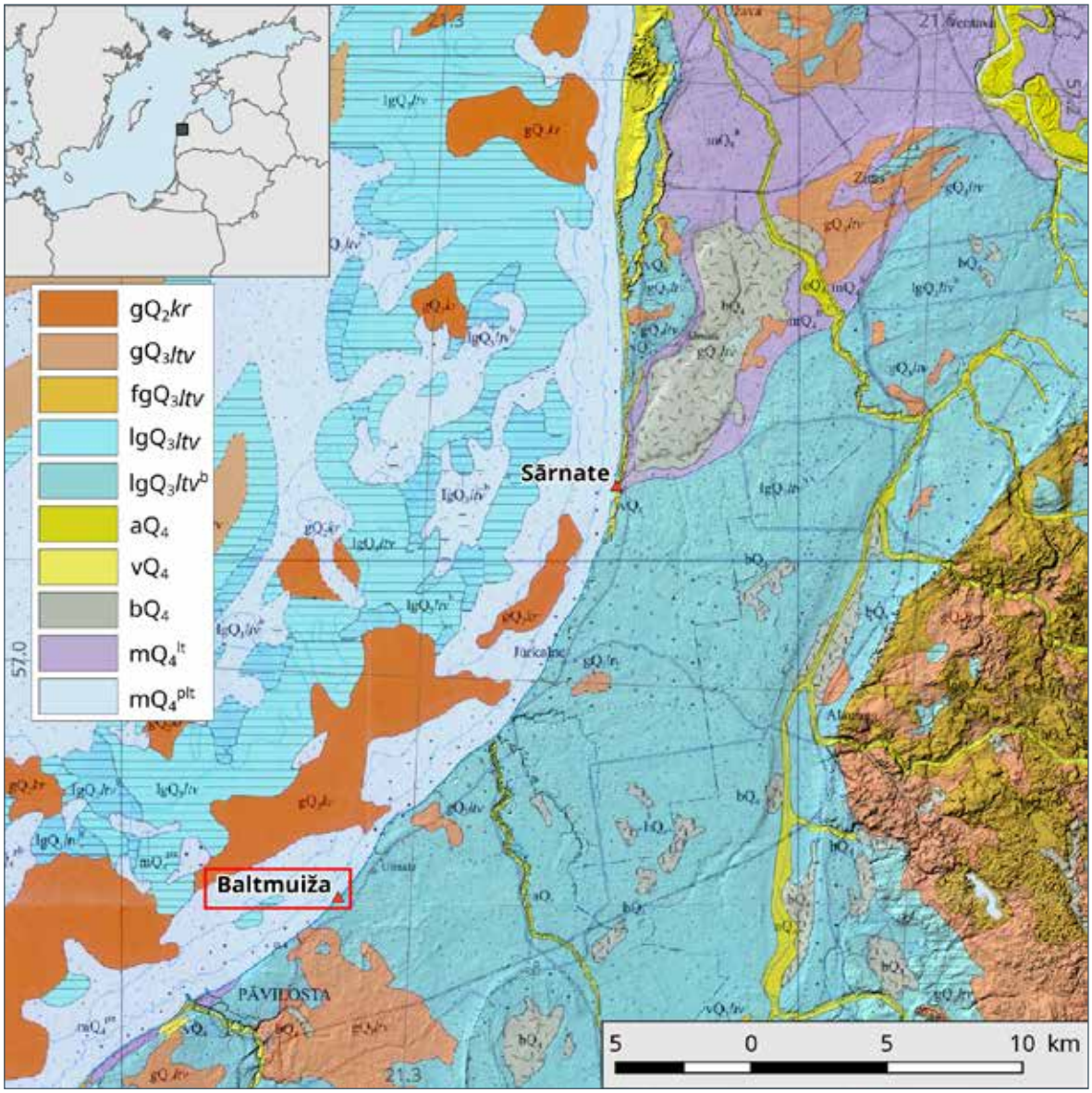

Fig. 1. Quaternary sediment map in the vicinity of Baltmuiža outcrop (Juškevičs et al. 1998)
AGE AND GENESIS OF SEDIMENTS: **gQ2kr** – glacigenic sediments (till) of Kurzeme (Saalian) glaciation, **gQ3ltv** – glacigenic sediments (till) of the Latvija (Weichselian) glaciation, **fgQ3ltv**–glaciofluvial sediments, **lgQ3ltv** – glaciolacustrine sediments, **lgQ3ltvb** – glaciolacustrine (Baltic Ice Lake) sediments, **aQ4** – Holocene river (alluvium) sediments, **vQ4** – Holocene aeolian sediments, **bQ4** – Holocene peat (bog) sediments, **mQ4lt** – Holocene marine (Litorina Sea) sediments, **mQ4plt** – Holocene marine (post-Litorina Sea) sediments.

SSDS features and origin

At least three continuous horizons containing soft-sediment deformation structures (SSDS 1–3) were observed along the sandy and silty succession outcropping in the upper part of the Baltmuiža cliff (Fig. 3). The overall width of the section reaches 15 m. Total thickness of the deformed horizons reaches 1.5 m.

The lowermost **horizon with SSDS 1** is mainly composed of sandy load casts (up to 12 cm) and silty injection structures. The distribution, shape and size of load casts varies irregularly along the layer. This horizon can be divided into a few subhorizons with different-scale load casts and pseudonodules, and separated from each other by deformed clay laminae (Fig. 3C, D). The top of the deformed horizon is erosional and irregular, that is overlain by ripple cross-laminated sand (Sr) and trough cross-stratifeid sand (St). The thickness of the SSDS1 horizon varies from 10 to 25 cm.

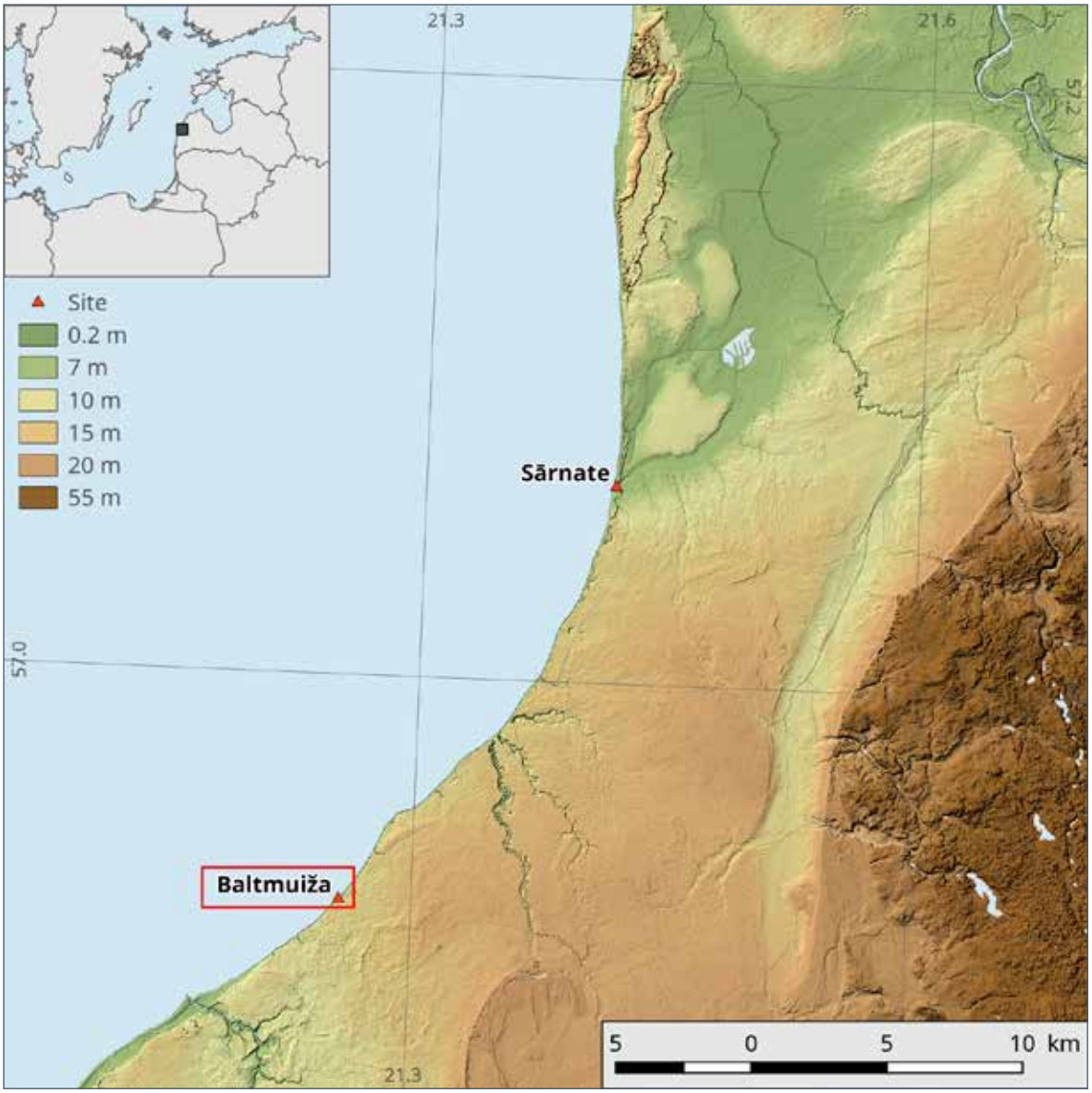

Fig. 2. Terrain of W Latvia coastal area between Baltmuiža and Sārnate. Based on LiDAR data of Latvian Geospatial Information Agency (2016)

In the middle, thinnest (up to 12 cm) **horizon with SSDS 2** sandy load casts as well as sandy-silty fluid-escape structures and injection structures were recognised. The thickness and extent of both – bottom and top boundaries of the horizon are variable and partially are clearly visible.

The third, uppermost deformed **horizon with SSDS 3** contains sandy load casts (up to 8 cm width), pseudonodules, detached layers as well as fluid-escape structures injecting the fluidized and liquefied silty sediments upwards. All of them are in smaller scale, comparing to the SSDS 1 and SSDS 2 horizons. The top boundary of the horizon is well-recognizable and continuous along its whole extent. That, up to 25 cm thick, uppermost horizon with SSDS 3 is overlain by the undeformed, planar and trough cross-stratified sand layer. Within the continuous series of several, similar in shape and size, sandy load structures along the uppermost horizon with SSDS 3, a primary structures can be observed (Fig. 3B-C). The structures within load casts are tilted, but not internally deformed, although the whole surrounding fine-grained sediments is arranged chaotically. This implies that the liquefaction, that directly triggered deformation processes, acted rapidly, what caused preservation of primary internal structures.

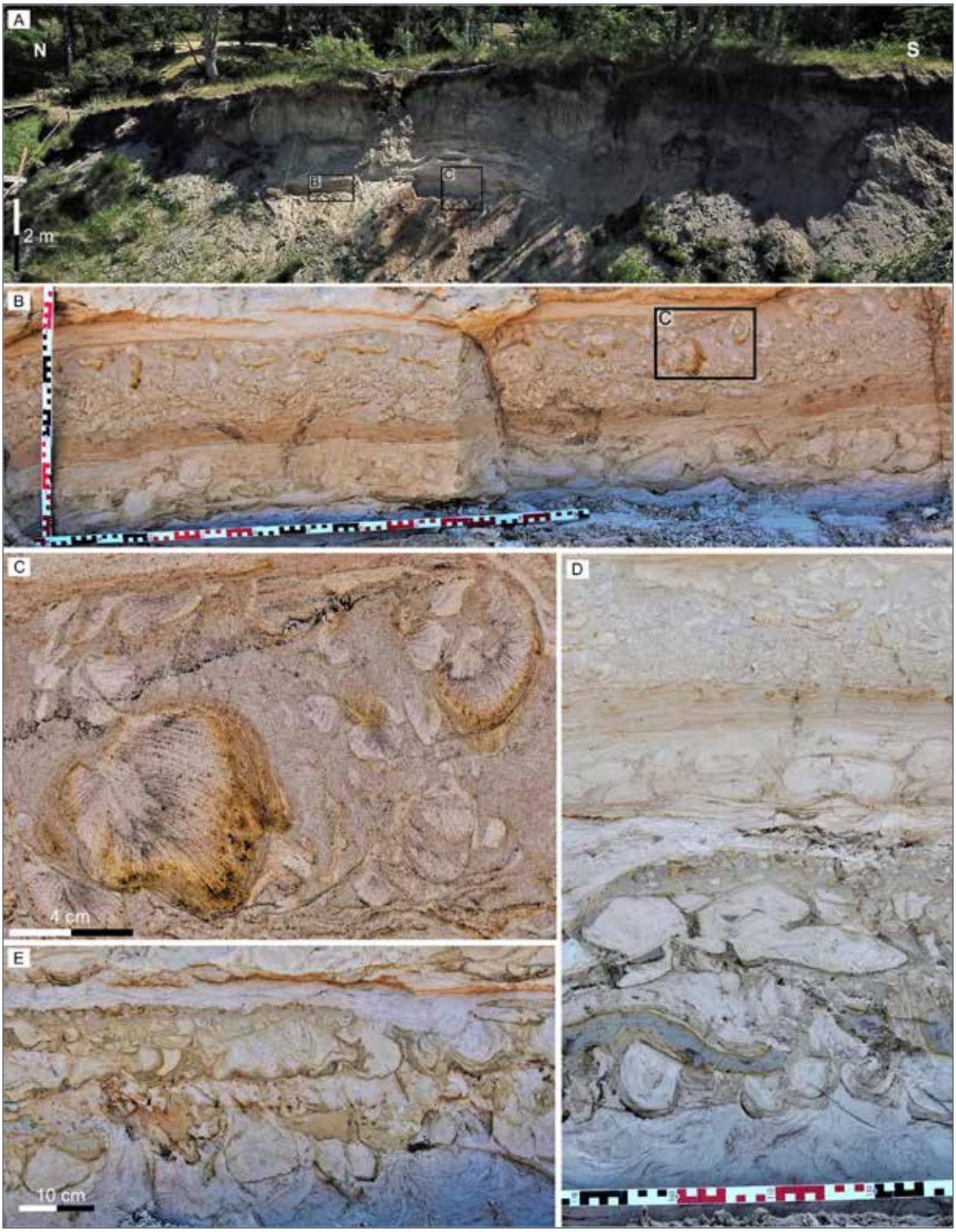

Fig. 3. The sedimentary succession of the Baltmuiža site

A: General view of the study section along the uppermost part of the cliff (aerial photo). **B:** Soft-sediment deformation structures within horizons of the upper part of SSDS 2 and the whole SSDS 3. **C:** Close-up view of the smaller scale load casts with undisturbed internal lamination and the surrounding sediments within SSDS 3. **D:** Vertical distribution of three deformed horizons (SSDS 1 – lower part, SSDS 2 – middle part, SSDS 3 – upper-part) with variable style, size and shape of deformation structures. **E:** Bigger scale load structures and accompanying injection structures in SSDS 1.

Soft-sediment deformation structures within all three described horizons were induced by liquefaction processes, that caused rapid vertical and horizontal interlayer movement of the fluidized sediment. However, the features of both – deformation structures and the whole horizons are differ-

entiated, what indicates variable conditions during events of sediment mobilization (caused, i.e. by slightly different lithology of sediments).

The process of deformation development within SSDS 1 is particularly interesting. The key role in the creation of the intrinsically complicated SSDS 1 (see subhorizons) played originally occurring thin clay laminae separating laminated sandy sediments, in the currently horizon SSDS 3. Most likely, deformations, e.g. load casts and pseudonodules developed independently in each subhorizons. Furthermore, when the pressure of water, in the sandy sediment 'trapped' between the clayey laminae, did not decrease – injection and breakthrough of the clayey laminae was evolved. This caused following deformations within sandy layer.

Comparing the size, extent and structural features, the described three horizons with SSDS seems not to be connected with commonly observed in the vicinity of the Baltmuiža site glaciotectonic deformations (large-scale diapirs, folds, reverse faults).

Possible trigger mechanisms

- Load structures and water-escape structures due to ice loading at the final stage of deglaciation
- Glaciotectonic deformations in the lower part of advancing ice sheet
- Local, seismic event (tremor) of moderate magnitude caused by glaciotectonic processes. Not triggered as the result of a fault reactivation.
- Glacioisostatic rebound affecting the crustal faults stability

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